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Percussion figures in crystals

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1. Introduction

When a polished sphere of hard steel is dropped from a height on the plane smooth surface of a thick slab of glass and rebounds therefrom, the impact results in a beautiful effect which is seen within the glass around the region of contact between the sphere and the slab. The phenomenon was described and illustrated by a set of photographs in a communication published many years ago under the title "Percussion figures in isotropic solids" in *Nature* of 9th October 1919. When an optical test-flat is laid on the surface of the glass slab over the region of impact, the nature of the permanent deformations resulting from the impact is very clearly revealed by the interference patterns seen in monochromatic light between the two surfaces. Photographs of these patterns were published in an article by the author on "The optical study of percussion figures" which appeared in the *Journal of the Optical Society of America* of April 1926. A more detailed study of the phenomena including especially a quantitative comparison between the facts of observation and the consequences of Hertz's well-known theory of impact appeared shortly afterwards in a paper by one of the author's collaborators in the *Indian Journal of Physics.*

It had long been the author's intention to investigate by similar methods the results of the impact of a steel sphere on single crystals of various materials. Only recently however did it become possible for this programme to be taken up and the present communication reports the results. The materials investigated were quartz, calcite, barytes, and felspar, and to make the study more complete, a few polycrystalline solids found in nature were also investigated. Photographs of the percussion figures obtained in the various cases are reproduced with the paper. The cases studied most fully are those of quartz and calcite. The results obtained with quartz are illustrated by figures 1 to 6 in plate I and figures 1 to 6 in plate II. Plates III–V illustrate the results obtained with the other solids.

2. Percussion figures in glass

Three photographs reproduced as figures 1, 2 and 3 in plate III exhibit the results of the impact of a steel sphere on the surface of a thick glass plate. Simple inspection reveals that the external surface of the slab remains uninjured by the impact except along a ring or annulus with a sharply defined inner boundary. Within the annulus is a clear circular area which evidently represents the region where the sphere and plate come into contact during the impact. From the ring or annulus a fracture spreads obliquely inwards within the glass in the form of a surface of revolution. Figure 1 in the plate is a lateral view of the fracture seen through the edge of the plate; its mirror-image as seen by internal reflection at the surface of the plate also appears in the photograph. Interference rings are exhibited by the fracture both by reflected and by transmitted light; their configuration indicates that the separation between the two faces of the fracture is a maximum at the surface of the plate and diminishes progressively to zero at its termination in the interior (figure 2). The interference pattern which is observed when a test-plate is laid on the surface is reproduced as figure 3. It shows the area of the percussion figure to consist of three distinct regions: (*a*) a circular central area which remains plane and undeformed, but exhibits a small permanent lowering of its level; (*b*) an annular region of fracture showing severe injury and (*c*) a sudden elevation of the surrounding area which slopes gradually down to the general level of the surface at the outer margin of the percussion figure; the last-mentioned feature is clearly a consequence of the internal fracture.

While the above is a general description, there are also other subsidiary features deserving of mention. When the circumstances of the impact are such that the pressure exerted by the sphere on the plate just suffices to produce a fracture, the circular ring-crack is sharp and well defined. On the other hand, when the velocity of the impinging sphere in relation to its size exceeds the minimum needed to cause a fracture, we have instead of a single circular crack, several cracks forming an annulus, the external diameter of which corresponds to the maximum area of contact, while the inner diameter is noticeably smaller. Subsidiary cracks also spread out in various directions along the surface of fracture interrupting its smooth continuity. Several of these can be seen in figure 2 in plate III.

3. Percussion figures in polycrystalline solids

Several naturally occurring solids are known which are polycrystalline in texture and which by reason of their mechanical strength find useful applications as building materials. Marble is one of the best known of them. It is however rather coarsely crystalline in its texture. Of greater interest from our present point of view is a material which may be described as a fine-grained limestone exhibiting varied colours and of which enormous quantities are quarried in Southern India for use as flooring tiles. According to the locality of its origin, the material is variously known as Cuddappah stone, Shahabad stone, Tandur stone, etc. It is easily split into slabs of the desired thickness and the surface of the slabs can be worked to any desired degree of perfection. Indeed, it can be polished so perfectly as to give regular interference fringes when a test-flat is laid on it.

Figures 4, 5 and 6 in plate III show the highly characteristic features of the percussion figures shown by the Tandur stones. Simple inspection by reflected light reveals a spherical dimple covering the area of contact between the sphere and the slab. A closer examination reveals a concentric set of sharply defined circular cracks lying on the slopes of the depression. One also observes a set of radial cracks spreading outwards from the edge of the cup-shaped depression. These features can be recognized in figure 4 of the plate. The interference patterns observed with a test-plate are of a totally different nature within the area of the depression and in the region outside it. They form a set of closely spaced circular rings within the depression (figure 6), while in the outer area they form a roughly hexagonal pattern the edges of which evidently correspond to the radial cracks spreading outwards (figure 5 in the plate).

A polished surface of marble shows very clearly the shallow depression produced by the impact of a steel sphere. Simultaneously also, the impact results in a visible breaking up of the texture of the marble, so much so that the entire area affected by it acquires a frosted appearance. We do not, however, observe either the circular or the radial cracks which are so conspicuous a feature in the case of the Tandur stones. The depressions in marble can also be made visible by laying a test-plate on the surface. This is shown in figures 3 and 4 in plate IV which refer to two different samples of marble.

Broadly speaking, it may be said that coarsely grained solids exhibit effects in impact which are similar to those exhibited by marble. This is illustrated by figures 5 and 6 in plate V which represent the deformations produced by impact as revealed by a test-plate. Figure 5 refers to the case of a black limestone akin to marble, while figure 6 represents the percussion figure in dolerite which is a hard and tough building stone capable of taking a high polish.

4. Percussion figures in quartz

Quartz does not exhibit any regular cleavages and shows only irregular fractures when broken under a hammer. In this respect it resembles glass. Prima facie therefore, we may expect quartz to exhibit percussion figures broadly resembling those observed with glass but differing therefrom in detail by reason of the fact that quartz is a crystal with anisotropic physical properties. These expectations are borne out by the facts. There are however some additional features of a rather surprising and unexpected nature.

In studying the percussion figures of crystals, it is obviously necessary that the surface on which the impact occurs is optically plane and has a specified orientation in relation to the axes of crystal symmetry. It is also necessary that the specimen employed is sufficiently massive in relation to the size of the impinging sphere. These conditions are fortunately attainable without much difficulty in the case of quartz. Specimens of adequate size and of reasonably good quality are obtainable which admit of being cut and polished in any desired direction. Three specimens of quartz were employed in the present investigation. One of them was a massive crystal weighing several kilograms. On this, a large surface about 20 cm × 10 cm normal to the optic axis was out and polished. A second face of nearly the same size parallel to a natural prismatic face was also ground and polished. Though the material was not of the highest optical quality, there were regions abutting on the two prepared surfaces which were quite clear and transparent and of sufficiently great extension in relation to the size of the percussion figures. The results observed are therefore worthy of confidence. The second specimen was a slab of crystal quartz about 20 cm × 15 cm and 5 cm thick, the faces of which were normal to the optic axis. One of the faces was carefully ground and polished. The third specimen employed was a crystal in its natural form exhibiting six prismatic faces, besides three large and three small rhombohedral faces. All these were ground and polished to perfection. The optical quality of the material was however rather poor.

Most of the detailed studies made refer to the case in which the surface on which the impact occurs is a basal section. Indeed, all the photographs reproduced in plates I and II refer to this situation. The reason for the choice made is obvious; for, since the impact in this case is along the optic axis of the crystal, we should expect the percussion figure to exhibit the maximum degree of symmetry. This expectation is borne out by the facts. Some visual observations were however also made for percussion figures on the prismatic and rhombohedral faces.

It is instructive to compare the photographs reproduced as figures 1 to 6 in plate I and as figures 1 to 6 in plate II which, as already stated, represent the percussion figures of quartz on a surface normal to the optic axis with figures 1 to 3 in plate III which show the percussion figures in glass. There are certain general similarities, but the differences are also striking and noteworthy. Alike in glass and in quartz, the impact results in the formation of cracks which commence on the surface around the margin of the area of contact and spread inwards into the material. But here all resemblance ends. The surface cracks in quartz are exceedingly fine and are seen under a magnifier as hair-lines clearly separated from each other, and there is otherwise no visible damage to the surface. The assembly of surface cracks is not circular in shape but resembles a hexagon with rounded edges. The fracture also spreads into the interior of quartz much more steeply than in the case of glass. This will be evident on a comparison of figure 4 in plate II which is an attempt to photograph the percussion figure in quartz as seen laterally with figure 1 in plate III which is the corresponding figure for glass. The fracture-surface in the interior of quartz rarely shows any interference colours either by reflection or in transmission, from which it is clear that the two faces of fracture are very close to each other. By reason of its steepness, however, the fracture can cut off the transmitted light and then appears dark. This is clearly seen in figures 1, 2 and 3 of plate I and also figure 3 of plate II. A light tilt of the fracture-surface in relation to the direction of the incident light however makes a large change in this respect (see figures 2 and 3 in plate I). The fracture-surface can also be seen and photographed by reflected light (figures 1 and 2 in plate II).

As will be evident from the photographs reproduced in the two plates, the percussion figure inside quartz exhibits only trigonal symmetry, and not hexagonal symmetry. The photographs, however, do not adequately picture the actual configuration of the fracture. The shape of the latter is perhaps best described as resembling a three-cornered hat. In other words, the fracture takes the form of three ribs with three flaps separating them. The flaps are much more easily seen by transmitted and reflected light than the ribs. Another and most interesting feature is the fine structure exhibited by the fracture within the quartz. One observes a radial fibrous structure and crossing this we have also a circumferential ribbing consisting of a great number of concentric circles which run all the way down from the surface to the termination of the fracture. The circumferential ribbing is most clearly seen in figure 1 of plate I and not quite so clearly in figures 1 and 2 of plate II. The radial structure is very clearly manifest in the two latter photographs.

As the fracture within the quartz exhibits only trigonal symmetry, the elevation of the surrounding surface may naturally also be expected to exhibit the same symmetry. This is manifest from the interference patterns observed when a test-plate is laid on the surface (see figures 4, 5 and 6 in plate I and figures 5 and 6 in plate II). The trigonal symmetry is particularly clear in the second of the two patterns reproduced in figure 6 in plate I.

It would not be profitable to attempt here any explanation or interpretation of the various features set out above. That the percussion figure for impact on a basal plane, in other words along the optic axis of quartz, exhibits only trigonal symmetry and not hexagonal symmetry is interesting, but not altogether surprising. For, we know that the optic axis of quartz is a three-fold axis and not a six-fold axis of symmetry of the structure.

With regard to the observations which have been made of the percussion figures on the prismatic and rhombohedral faces, it will suffice here to remark that they do not exhibit the trigonal symmetry described and illustrated in plates I and II. In other respects, however, they exhibit features very similar to those set forth above. Each of the two cases exhibits special features of its own. But the observations made are not sufficiently numerous and trustworthy to justify a detailed description or discussion of the same.

5. Percussion figures in calcite

A calcite crystal in its natural form as a rhomb with edge-lengths 8 cm × 6 cm × 4 cm was employed in the study. Though the material was not of the highest optical quality throughout its volume, a region adjacent to one of the larger faces (8 cm × 6 cm) was clear and transparent to a considerable depth. Accordingly, this particular face was ground and polished and utilized for the production of the percussion figures. One of the adjacent faces (6 cm × 4 cm) was also ground and polished so as to permit of the interior of the crystal being viewed through it. In view of the small size of the specimen, the steel sphere employed was also small, about a centimetre in diameter. It had a highly polished surface and was dropped on the polished face of the rhomb from different heights at eight different points sufficiently remote from each other to ensure the absence of any mutual interference.

Percussion figures are observed around each of the chosen points of impact. They are conspicuous when the faces of the rhomb are viewed by reflected light, and they can also be seen to penetrate into the crystal when viewed longitudinally and also when observed laterally through the adjacent polished face. All the eight figures exhibit a general similarity with each other, though their sizes are different, since they diminish with the velocity of impact. They are all similarly orientated on the face of the rhomb and the configuration of each is symmetric about a plane normal to the face of the crystal which makes equal angles with its two rhombohedral edges. But they do not exhibit any symmetry with respect to a perpendicular plane and are indeed strikingly different on the two sides of it. The actual region of contact between the sphere and the crystal can be readily recognized by the fact that it appears relatively dark as seen by reflected light in comparison with the brilliant display of colours all round. It is also evident on a careful examination that it is slightly depressed in level below the original surface of the crystal.

Viewed by reflected daylight, the percussion figures exhibit a complex pattern of interference colours and fringes. The interferences are also conspicuously visible in monochromatic light. A photograph of the same is reproduced as figure 1 in plate IV. When an optical test-flat is laid on the calcite and allowed to settle down so that it comes into close contact with the crystal face, the interference pattern seen differs very little indeed from that observed without the test-plate. This fact is evident on a comparison of figure 1 in plate IV with figure 2 in the same plate, the latter representing the fringes seen when the test-plate has been laid on. If there are any fringes between the test-plate and the crystal, they are so faint and broad that their superposition on the closely spaced fringes in the interior makes little difference to what is actually observed.

It is well-known that calcite has three planes of easy cleavage parallel to the three faces of the rhombohedron and that it also possesses three glide planes each containing one of the rhombohedral edges and equally inclined to the other two.

An examination of the percussion figures in calcite reveals that the two cleavage planes intersecting the face on which the impact occurs play an important role in determining the results of the impact. It is observed that on either side of the area of contact between the sphere and the crystal, two cleavages making an acute angle with each other develop and extend outwards from the edges of that area. These cleavages are clearly visible on the face of the crystal, and they sharply limit the areas within which the fracture develops and spreads inwards into the crystal. Indeed, the pattern of reflected colours as seen in daylight and the interference pattern as seen by monochromatic light manifest themselves wholly within the limits set by these two cleavages. These features can be clearly recognized in figure 1 of plate IV. A further and most interesting feature is the appearance of a whole series of parallel lines outside the region of contact and on only one side of it and which extend over a considerable area of the pattern. These lines are equally inclined to the two sets of cleavages and cut across the curved interference bands exhibited by the fracture. We may explain them as due to glides occurring in the crystal along the direction of the third rhombohedral edge. The direction of the glide deviates greatly from the normal to the crystal face on which the impact occurs and hence also from the direction of impact. This may explain why the fracture-surface within the crystal extends much more in the forward direction than in the backward.

6. Percussion figures in barytes

The specimen of barytes employed was translucent with a faint bluish tinge. Its original shape as a crystal was that of a parallelopiped, four of whose faces were nearly rectangular, while the other two deviated sensibly from that shape. An artificial face of larger dimensions was obtained by cutting through the specimen in a direction making 45° with the rectangular faces; it was then ground and finely polished. In view of the small size of the specimen, the steel ball used had also to be quite small, only about 6 mm in diameter. It was dropped from various heights and the percussion figures thus obtained were critically examined.

The effects produced by the impact may be summed up as follows. Firstly, we have a visible dimple or depression left on the surface. There is also a general disturbance of the level of the crystal face around the point of impact, and this is not spherically symmetrical around the region of impact. We have also noteworthy changes in the interior of the crystal which result in a brilliant reflection appearing in certain directions, while it appears dark in other directions. This effect varies greatly with the direction of illumination and the direction of observation, some areas appearing dark in certain circumstances and others bright and *vice versa.* A remarkable lack of symmetry is exhibited by the effect. Merely turning round the specimen through 180° under oblique illumination and normal observation results in all the areas which appear dark becoming bright and *vice versa.*

The internal reflections exhibited by one of the patterns is reproduced as figure 5 in plate IV. As both the illumination and the observation were normal, the special features mentioned above are not exhibited. Seen under oblique illumination, the figure resembles a butterfly with outstretched wings and tail, the head being bright and the tail and wings dark or *vice versa.* The changes in the interior—presumably in the nature of fractures—are accompanied by changes in the external level of the surface. These latter are revealed by the interference fringes observed when a test-plate is put on the specimen. This is illustrated by figure 6 in plate IV. This has the same orientation as figure 5, the latter being the figure as seen by reflected light.

7. The percussion figures in felspar

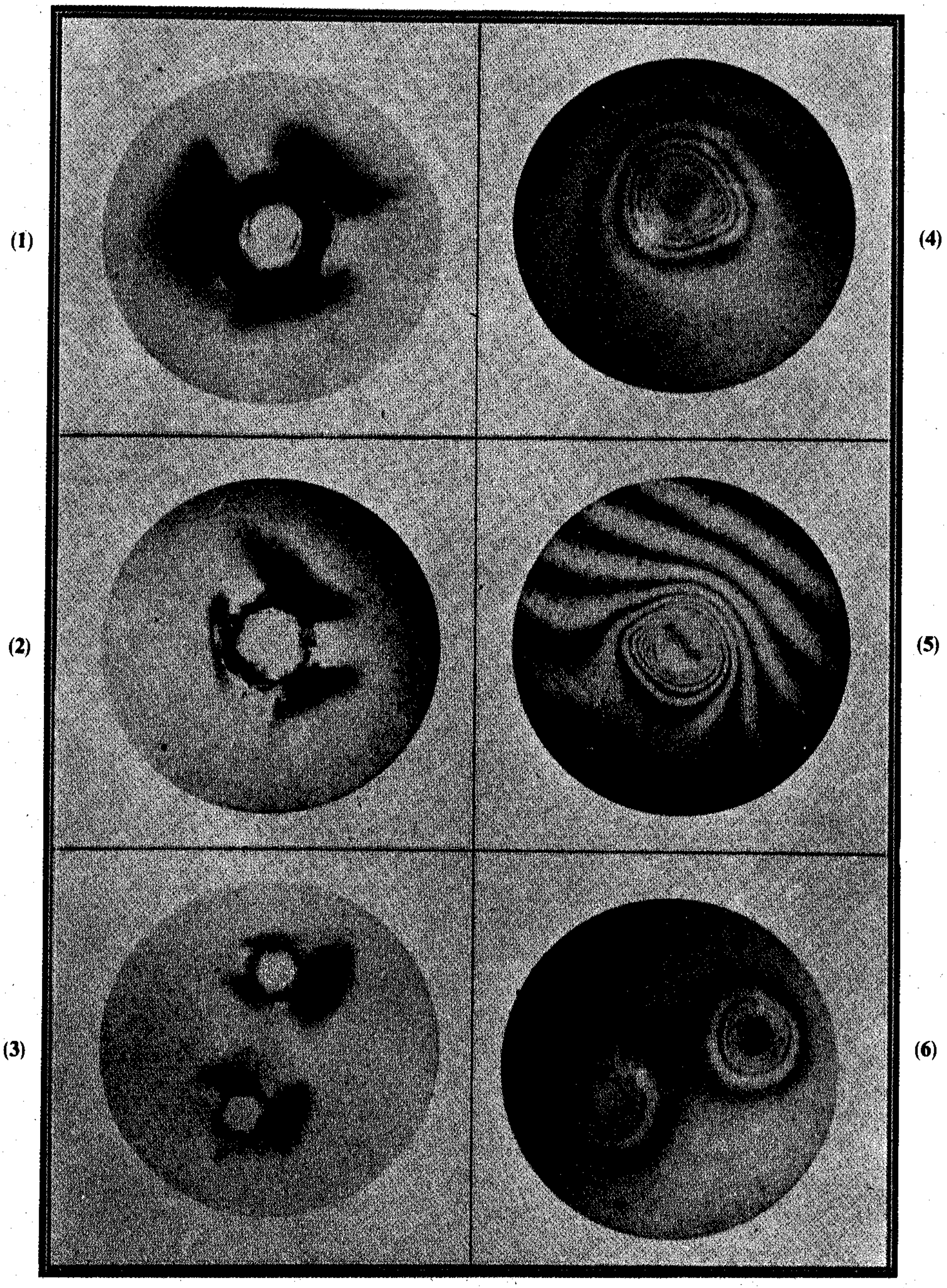
Specimens of felspar of large size are readily available exhibiting the natural faces of the crystal. These faces can be ground and polished so as to be optically plane. Thus, felspar lends itself readily to an exact study of the results of impact on crystal surfaces of known orientation. Unfortunately, however, it is not easy to obtain crystals of any appreciable size which are *optically clear.* The observations have accordingly to be confined to those features resulting from impact which are *externally* observable. This makes it rather difficult to make any detailed analysis of the results of impact in terms of crystal structure and orientation.

A highly characteristic effect exhibited by felspar and produced by the impact of a steel sphere on a natural crystal face is illustrated in figure 1 in plate V. Viewed by oblique illumination, the area of contact appears as a dark crescent surrounded by a bright crescent beyond it. Careful examination shows that the bright crescent is an internal reflection. Merely turning round the specimen through 180° causes the reflection to disappear. The reflection presumably arises from a fracture in the interior of the felspar produced by the impact. This naturally also results in an elevation of the surface and this is revealed by placing a test-plate on the surface. We then observe an asymmetric distribution of interference rings around the region of the impact. Five such patterns are seen in figures 2 and 3 in plate V. It will be noticed that the interference patterns are all similarly orientated, indicating that the phenomenon is definitely related to the crystal structure of the material. Figure 4 is a photograph of the interference pattern exhibited by the percussion figure on a different natural face of a felspar crystal. It will be seen that it has an altogether different character from those reproduced in figures 2 and 3 in the same plate.

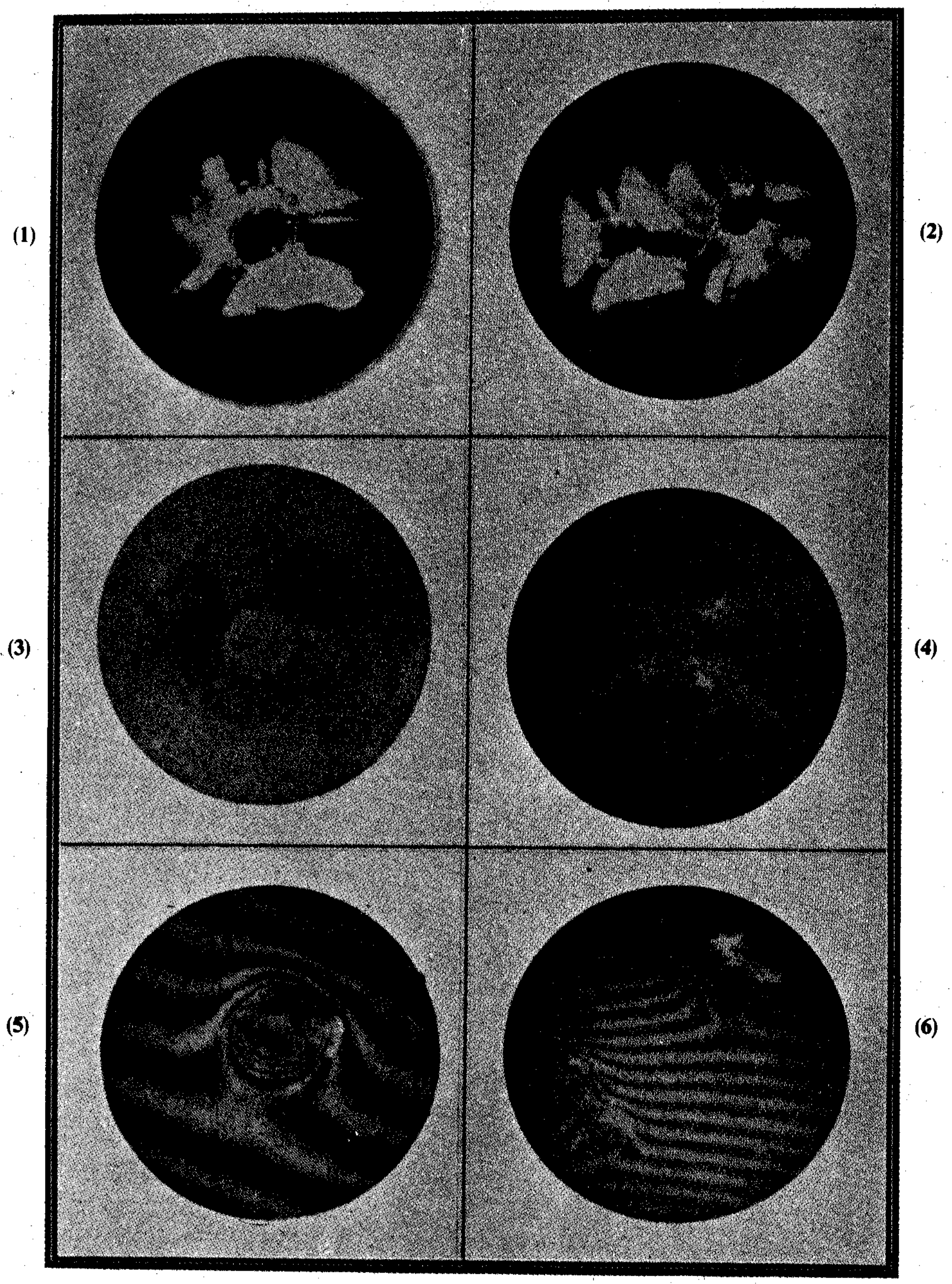
The preparation of the material employed in these studies and of the pictures which illustrate the paper required much painstaking labour. The work was undertaken and successfully carried out by my research assistant Mr J Padmanabhan.

Summary

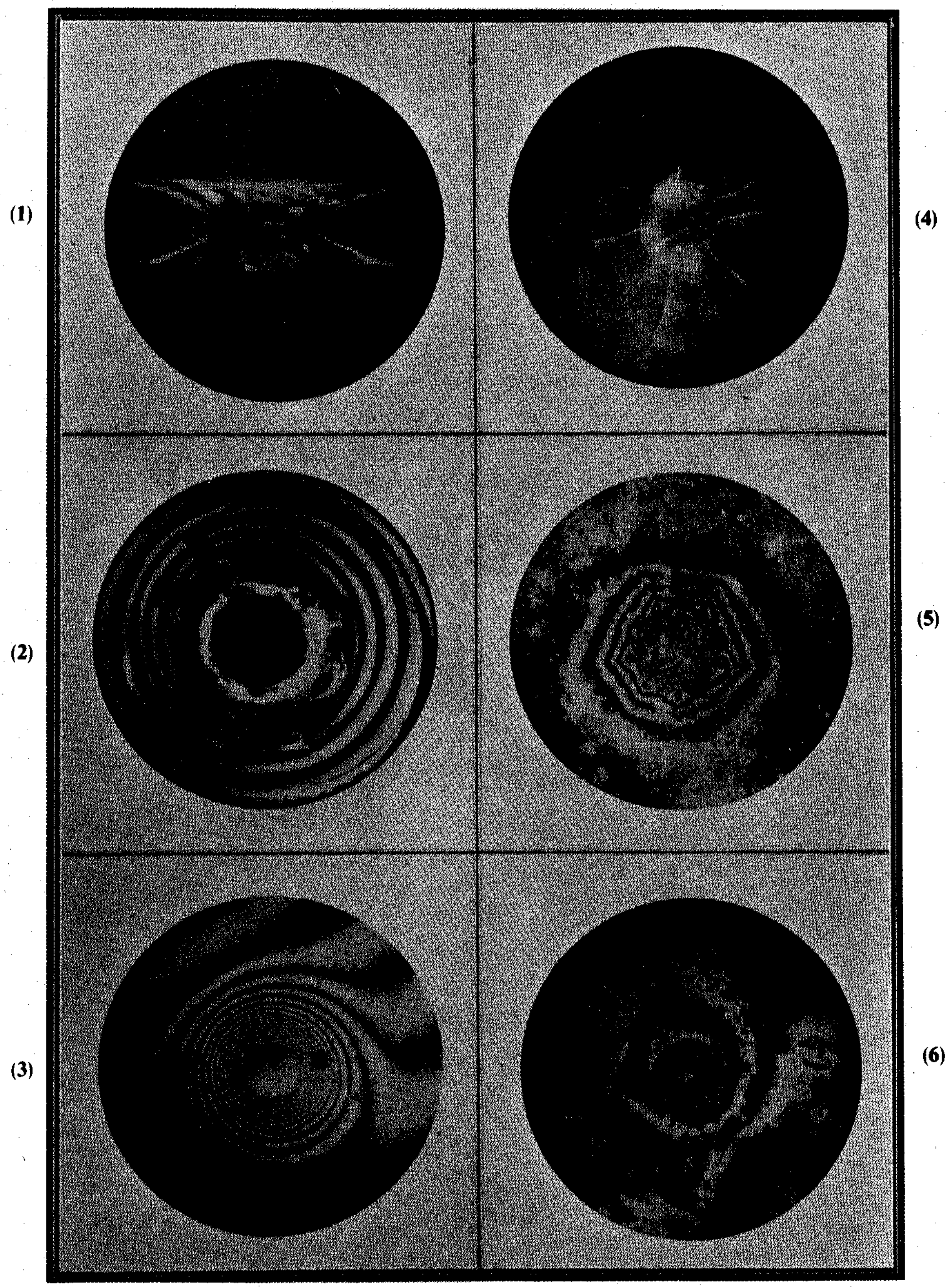
The impact of a hard steel sphere on the optically polished surface of a solid results in a permanent deformation of the surface and also produces fractures or rearrangements in the interior of the solid. These have been studied with crystals of quartz, calcite, barytes and felspar and also with a few polycrystalline solids. The results of the study show clearly that the nature of the percussion figure exhibited by a solid is a characteristic property of the material and is related to its inner structure and symmetry. The paper is illustrated by a series of photographs.



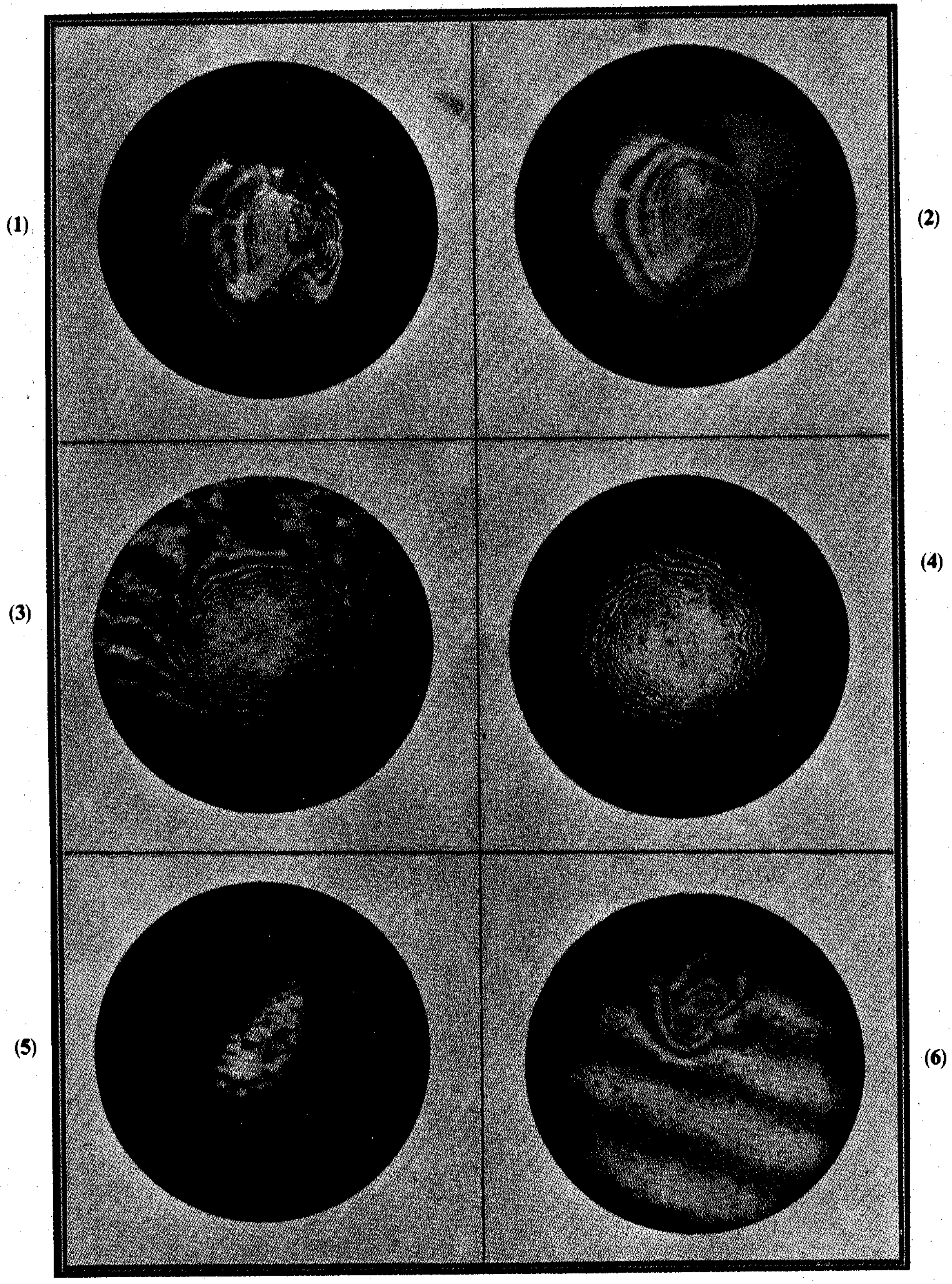
Figures 1–6.
Plate I. Percussion figures in quartz.



Figures 1–6.
Plate II. Percussion figures in quartz.

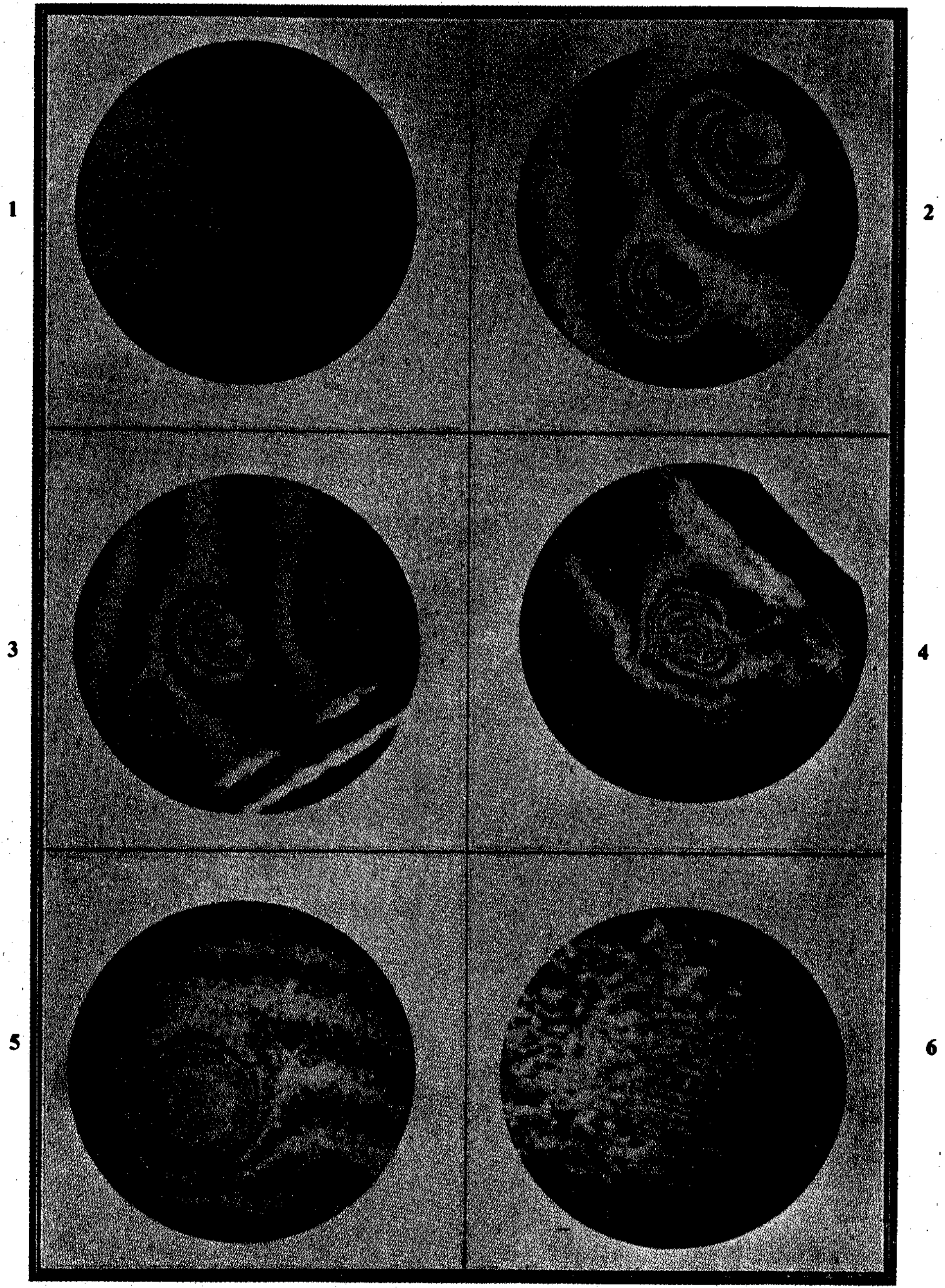


Figures 1–6.
Plate III. Percussion figures: figures 1, 2, 3 in glass and figures 4, 5, 6 in polycrystalline limestone.



Figures 1–6.

Plate IV. Percussion figures: figures 1 and 2 in calcite; figures 3 and 4 in marble; figures 5 and 6 in barytes.



Figures 1–6.

Plate V. Percussion figures: figures 1, 2, 3, 4 in felspar; figure 5, hard limestone; figure 6, dolerite.